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Frequency Adaptability of Harmonics Controllers for Grid-Interfaced Converters

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A wider spread adoption of power electronic converters interfaced renewable energy systems has brought more attention to harmonic issues to the electrical grid, and means are taken to improve it in the control. More advanced closed-loop harmonic controllers are thus demanded to enhance the renewable energy integration in order to be grid-friendly. However, usually being treated as a constant factor in the design of harmonic controllers, the grid frequency varies with the generation-load imbalance, and thus may lead to deterioration of the power quality. This paper explores the frequency sensitivity of the most popular harmonic controllers for grid-interfaced converters. The frequency adaptability of these harmonic controllers is evaluated in the presence of a variable grid frequency within a specified reasonable range, e.g., $\pm 1\%$ of the nominal grid frequency (50 Hz). Solutions to the improvement of the frequency variation immunity of the discussed harmonic controllers are also emphasized. Case studies of a single-phase grid-connected photovoltaic system are provided to verify the analysis.

Keywords: renewable energy; power electronics; grid converters; pulse width modulation (PWM); harmonics; frequency variation; current controller; harmonic controller

1. Introduction

Renewable energy resources, in particular PhotoVoltaic (PV) and Wind Turbine Systems (WTS), have experienced a significant increase in terms of worldwide total installed capacity in the past decade, and they will play an even important role in the future energy mix in most countries (IEA, 2014; REN21, 2014). However, beyond decarbonization from massive renewable energy systems enabled by the power electronics technology (Blaabjerg, Liserre, & Ma, 2012; Blaabjerg, Ma, & Yang, 2014), side-effects like harmonic emissions to the highly renewable-powered grid are becoming more challenging than ever before. One of the quality degradation causes lies in the intermittent nature of renewable energy sources - the output power is fluctuating and it is strongly dependent on the atmospheric conditions (Gonzalez, Romero, Minambres, Guerrero, & Gonzalez, 2014; Kopicka, Ptacek, & Toman, 2014; Rodway, Musilek, Misak, & Prokop, 2013). Power smoothing strategies by using energy storage systems (Katiraei & Agüero, 2011; Li, Hui, & Lai, 2013; Somayajula & Crow, 2014; Wang, Ciobotaru, & Agelidis, 2014) can alleviate harmonic distortions to some extent. However, the main reason for harmonic injections is the usage of Pulse Width Modulation (PWM) based power converters that will produce e.g. switching frequency harmonics, as the interface to the grid, which is also distorted (mainly low-order harmonics) by non-linear loads, e.g. diode rectifier loads. Advanced harmonic controllers or strategies for grid-interfaced power converters, e.g. predictive controller, repetitive controller, and resonant controller, and shunt active power filters have been developed to enhance the integration of renewable energy.

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For instance, applications of non-linear controllers like hysteresis controller in grid-interfaced power converters have been witnessed in the past (Blaabjerg, Teodorescu, Liserre, & Timbus, 2006; Timbus, Liserre, Teodorescu, Rodriguez, & Blaabjerg, 2009). The main obstacle to further expand its application lies in the high sampling rate requirement of the controller (e.g. Digital Signal Processors, DSP) and its complexity (Blaabjerg et al., 2006). In contrast, the linear controllers are of more simplicity and more easy to implement in cost-effective micro-controllers. Such harmonic controllers can be implemented in different reference frames, i.e. a) abc -natural reference frame, b) $\alpha\beta$ -stationary reference frame, and c) dq -synchronous reference frame. The well-known Proportional Integrator (PI) controller is enabled by the Clarke ($abc \rightarrow \alpha\beta$) and Park ($\alpha\beta \rightarrow dq$) transformations, and thus implemented in the dq -reference frame. It has also been reported in (Twining & Holmes, 2003) that, the PI controllers can also be applied to the control of grid-interfaced converters in abc -reference frame, which contributes to an increased complexity. Similarly, the usage of PI controllers in the $\alpha\beta$ -reference will also deteriorate the current quality. As a result, the Proportional Resonant (PR) controller and the Repetitive controller (RC) (Chen, Zhang, & Qian, 2013; Freijedo et al., 2011; Hornik & Zhong, 2011; Timbus, Ciobotaru, Teodorescu, & Blaabjerg, 2006; Yepes et al., 2010; Yepes, Freijedo, Lopez, & Doval-Gandoy, 2011; Zhou et al., 2006; Zhou, Yang, Blaabjerg, & Wang, 2015) are more favorable in the control of grid-interfaced power converters, since they can achieve zero-error tracking of sinusoidal signals including harmonics in accordance to the Internal Model Principle (IMP) (Muraca, 2014). Additionally, harmonic compensators are required in order to achieve higher power quality, and thus hybrid controllers have been developed (Liserre, Teodorescu, & Blaabjerg, 2006; Rashed, Klumpner, & Asher, 2013).

In the case of a constant grid frequency, most of the aforementioned current (harmonic) controllers can attain a satisfactory Total Harmonic Distortion (THD) defined in the grid interconnection requirements (IEC Standard, 1995, 2002; IEEE Standard, 2000). However, due to the intermittent and fluctuating power of renewable energy systems, the grid frequency cannot always maintain a constant value in accordance to the droop characteristic of the grid frequency and the active power injection (Serban & Marinescu, 2014; Yang et al., 2015; Zou, Zhou, Wang, & Cheng, 2014). The frequency deviations within a certain range, e.g., $\pm 1\%$ of the nominal grid frequency (Christiansen & Johnsen, 2006), will possibly affect the performance of the harmonic controllers, and thus may deteriorate the power quality. As it has been mentioned above, although many harmonic controllers can meet the THD requirement when the renewable energy system is connected to grid, a qualitative analysis of the frequency variation immunity of those controllers remains. There is still a lack of quantitative discussions on how the controllers will be affected by even smaller grid frequency variations (e.g., ± 0.2 Hz). As a consequence, those unaddressed issues have hindered the advancement of robust and frequency-adaptive harmonic controllers for grid-interfaced power electronics converters.

In view of the above discussions, the focus of this paper has been put on the frequency sensitivity analysis of selected harmonic controllers. Firstly, Section 2 presents typical control strategies for both single-phase and three-phase grid-interfaced power converters, followed by the implementation of the selected harmonic controllers in these control strategies. The frequency adaptability of these harmonic controllers is then addressed in terms of harmonic rejection capability when the grid suffers from frequency variations in Section 3. Based on the analysis, emphasises on how to improve the frequency variation immunity has also been presented to initiate further research perspectives. In order to verify the frequency adaptability, experimental tests on a single-phase grid-connected PV inverter systems have been provided in Section 4 before concluding this paper.

2. General Control of Grid-Connected Renewable Energy Systems

Depending on the renewable energy types and also the power ratings, several grid-connected configurations are possible. A general structure of grid-connected renewable energy systems is shown in Figure 1, where the power electronics system is the key to efficiently and reliably realize such an

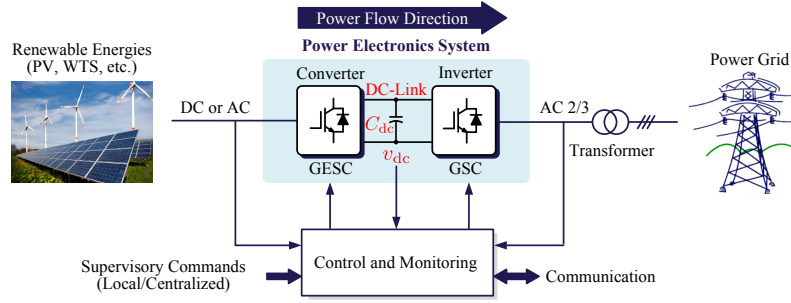


Figure 1. General configuration of renewable energy with grid-interfaced power converters.

energy conversion from the renewable energy source. It can be observed that the grid-connected system consists of two conversion stages - a Generator Side Converter (GES) and a Grid-Side Converter (GSC), which are linked by a DC-Link. Specifically, the GES (e.g. a DC/DC converter in grid-connected PV systems) is adopted to implement a Maximum Power Point Tracking (MPPT) algorithm in order to maximize the energy extraction from the renewable energy source (e.g., PV panels). In contrast, the GSC is more responsible for controlling the capacitor voltage, v_{dc} , at the DC-Link, and injecting the power to the grid. Power quality issues are also achieved in the control of the inverter stage. Since the focus of this paper has been set on the grid-interfaced power converters, where the responsibility of the current quality is normally achieved by enhancing the harmonic controllers, the following presents the general control of the grid-interfaced power converters both for single-phase and three-phase PV inverter systems.

2.1 Control of Three-Phase Grid-Interfaced Power Converters

As mentioned earlier, the GES focus mainly on the maximization of the renewable energy, while the GSC is aimed at a proper power injection of a satisfactory power quality. Typically, the control of grid-interfaced converters consists of two-cascaded loops (Blaabjerg et al., 2006): an outer voltage/power control loop for current reference generation and an inner current control loop for injected grid current shaping.

For a three-phase system, control of grid-interfaced power converters (i.e., the GSC) can be done in different reference frames. Figure 2 shows in details different control structures of the GSC for a three-phase grid-connected PV system. In the consideration of implementations, the PI-controller based GSC control in the dq -reference frame may not be the optimal one since it requires complicated transformations and current decoupling (ωL_t with $L_t = L_1 + L_2$), as shown in Figure 2(c). In contrast to the control of the grid-interfaced power converters in the abc -reference frame, the GSC control in the $\alpha\beta$ -reference frame is simpler in terms of less control variables (i.e., i_α and i_β) and thus has less parameter tuning burden. In that case, the PI controller is not suitable to use either as the fundamental current controller, due to its poor tracking performance of variable sinusoidal signals. Alternatively, a Dead-Beat (DB) $G_{DB}(z)$ algorithm as a predictive controller and the PR controller $G_{PR}(s)$ can be adopted as the fundamental current controller (Teodorescu, Liserre, & Rodriguez, 2011). Those fundamental current controllers can be expressed in the z -domain and in the s -domain respectively as,

$$G_{DB}(z) = \frac{z^{-1}}{(1 - z^{-1})G_f(z)G_d(z)} \quad (1)$$

$$G_{PR}(s) = k_p + \frac{k_i s}{s^2 + (\omega_0)^2} \quad (2)$$

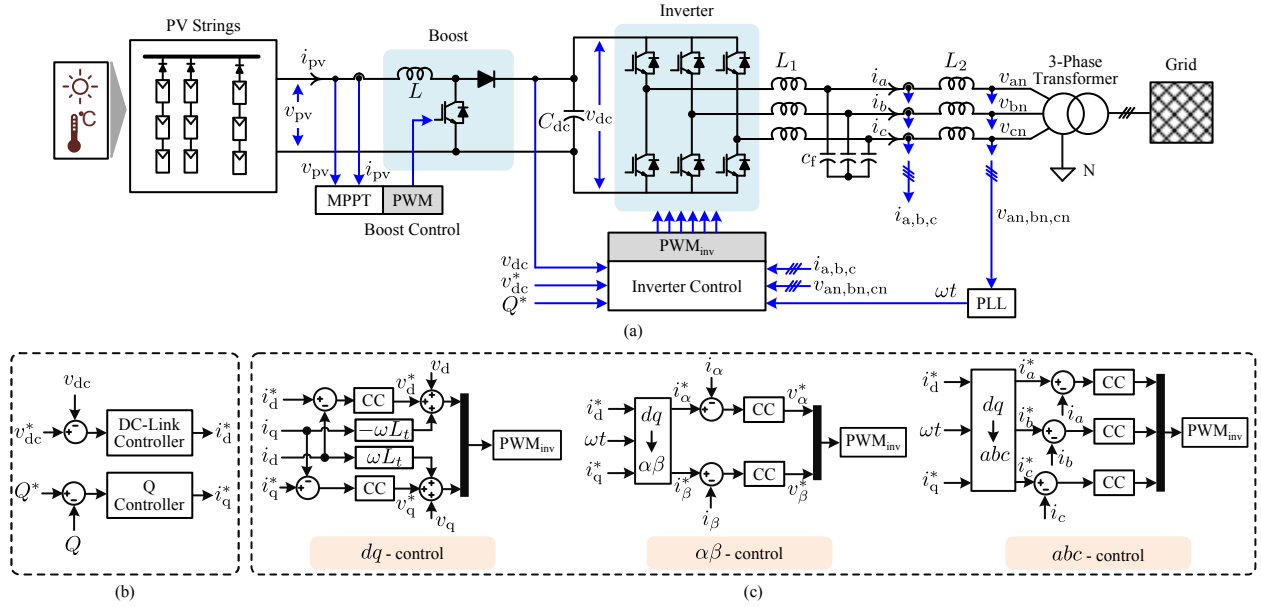


Figure 2. Grid-interfaced inverter control of a three-phase PV systems with two cascaded loops (CC - Current Controller): (a) Hardware schematic, (b) outer control loop for current references, and (c) inner current control loop in different reference frames.

in which $G_f(z)$ is the filter model in the digital form, $G_d(z)$ is the PWM delay, k_p , k_i are the control gains of the PR controller, and $\omega_0 = 2\pi f_0$ is the nominal grid angular frequency with f_0 being the nominal grid frequency.

It can be observed in (1) that the DB controller exhibits a very fast response (i.e., theoretically one-sampling period) and there is no requirement of parameter tuning, but the main disadvantage of the DB controller lies in the filter parameter mismatches (Blaabjerg et al., 2006; Nishida, Ahmed, & Nakaoka, 2014; Timbus et al., 2009). In contrast, the PR controller is more complicated since it requires the knowledge of the grid frequency and there are two parameters to design. However, the PR controller is more robust to follow the fundamental periodical signal effectively, and it is more immune to grid background distortions. It can be foreseen that the PR controller is more sensitive to the grid frequency deviations, since its performance is dependent on the resonant frequency (i.e., the grid frequency), when comparing with the DB controller according to (1) and (2).

2.2 Control of Single-Phase Grid-Interfaced Power Converters

In contrast to the GSC control of three-phase systems, the controllability of the single-phase GSC is reduced, since only the grid voltage v_g , grid current i_g , and the DC-link voltage v_{dc} are controlled (measured) during operation, as it is shown in Figure 3. However, a Quadrature Signal Generation (QSG) system, which creates a virtual system v_g^\perp in respect to the real single-phase system v_g , can enable the control of single-phase grid-interfaced converters in the dq -reference frame, as shown in Figure 3(b), where PI controllers can be used. According to the single-phase PQ theory (Saitou & Shimizu, 2002), the reference grid current i_g^* can be expressed as,

$$i_g^* = \frac{2}{V_{gm}^2} [v_g \ v_g^\perp] \begin{bmatrix} P^* \\ Q^* \end{bmatrix} \quad (3)$$

where $V_{gm}^2 = v_g^2 + (v_g^\perp)^2$, P^* and Q^* are the reference power, and v_g^\perp is the in-quadrature signal in respect to the grid voltage v_g . Thus, the GSC control can be implemented in the $\alpha\beta$ -reference frame, as it is shown in Figure 3(c). Moreover, the reactive power injection can be achieved flexibly with this control method.

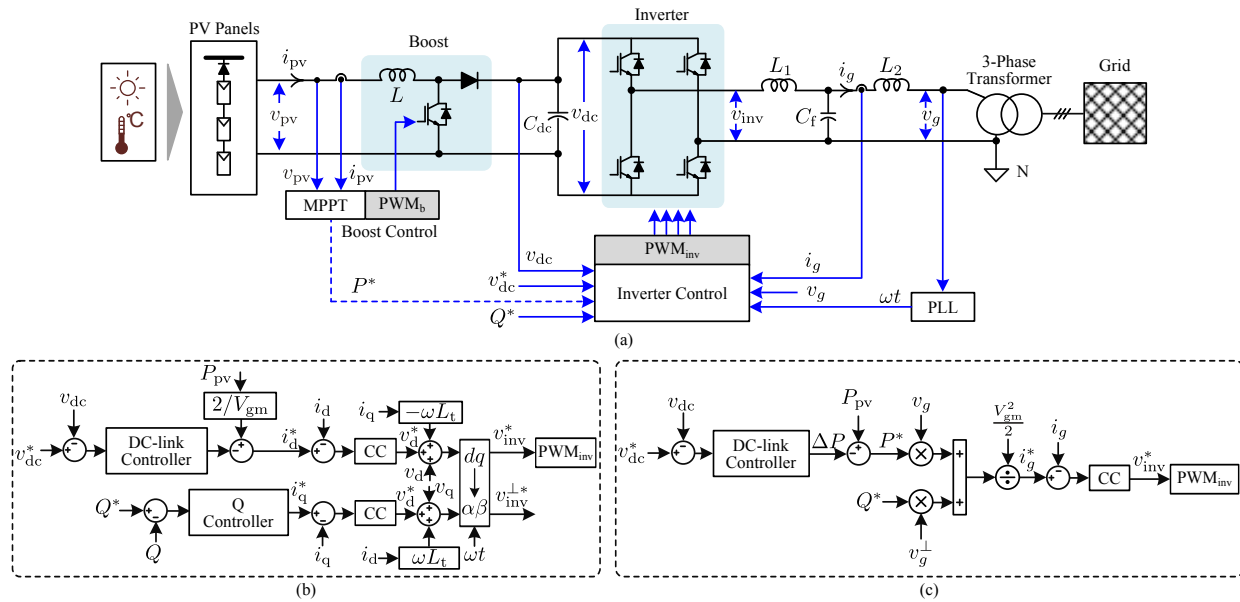


Figure 3. Grid-interfaced inverter control of a single-phase PV systems with two cascaded loops (P_{PV} - PV output power, CC - Current Controller, $L_t = L_1 + L_2$): (a) Hardware schematic, (b) control in the dq -reference frame, and (c) control in the $\alpha\beta$ -reference frame.

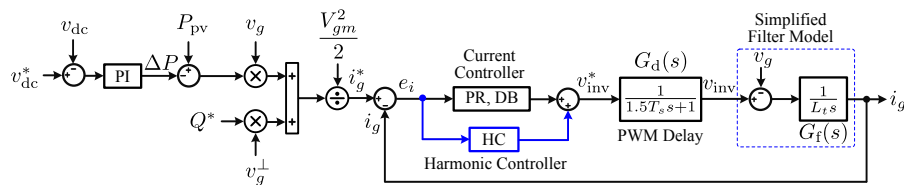


Figure 4. Closed-loop control system of a single-phase grid-interfaced PV inverter (PR - Proportional Resonant, DB - Dead-Beat, HC - Harmonic Controller), where the *LCL* filter is simply modeled as an *L* filter (Liserre et al., 2005; Yepes, Freijeido, Lopez, & Doval-Gandoy, 2011).

It is clearly observed in Figure 3 that the control of the GSC in single-phase systems in the $\alpha\beta$ -reference frames is of much simplicity, where only one current controller is required and the above mentioned PR controller and DB controller are applicable. A PI controller can be used to regulate the DC-Link voltage. The closed-loop control system is then given as shown in Figure 4 with T_s being the sampling period. The closed loop system has been used for the frequency adaptability analysis of the harmonic controllers in the following. It should be noted that, an advanced synchronization algorithm (e.g., the Phase Locked Loop (PLL) system), especially for a single-phase system, can enhance the control performance of the GSC (Blaabjerg et al., 2006; Muraca, 2014).

3. Frequency Adaptability of Harmonics Controllers

3.1 Harmonic Controllers for Grid-Interfaced Power Converters

When the renewable energy systems are connected to the grid, the power quality of the injected current can be enhanced by means of introducing harmonic compensators (Harmonic Controllers, HC) as it is shown in Figure 4. It has been mentioned previously that the harmonic control is achieved in the current controller and it can be implemented in different reference frames. For example, PI based harmonic controllers can be implemented in the dq -reference frame in a cascaded way, but the complexity is also noticeable (Blaabjerg et al., 2006). Alternatively, the resonant controller (Freijedo et al., 2011; Timbus et al., 2006; Twining & Holmes, 2003; Yepes et al., 2010;

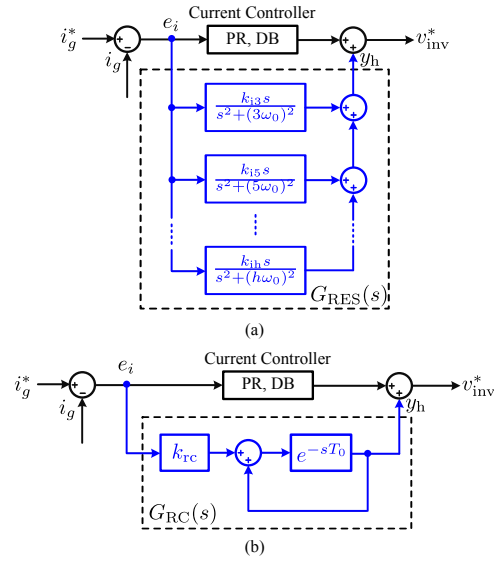


Figure 5. Internal model principle based harmonic controllers for grid-interfaced power converters (PR - Proportional Resonant, DB - Dead-Beat): (a) parallel resonant controllers and (b) repetitive controller.

Yepes, Freijedo, Lopez, & Doval-Gandoy, 2011) can approach infinite gain in the open-loop system at the resonant frequencies, and thus achieve zero tracking error in the closed-loop system for any sinusoidal signal at the corresponding resonant frequencies, offering a flexible way to mitigate harmonic injections. Cascaded multiple parallel RESonant (RES) based harmonic compensators with a PR controller can be a good solution for selective harmonic control in grid-interfaced converters. This cascaded HC can be given as,

$$G_{RES}(s) = \sum_h \frac{k_{ih}s}{s^2 + \omega_h^2} \quad (4)$$

where k_{ih} is the control gain of the resonant controller with h being the harmonic order, and ω_h is the harmonic frequency. Theoretically, $\omega_h = h\omega_0 = h \cdot 2\pi f_0$ with f_0 being the nominal grid frequency estimated by a PLL system, so that the harmonics can be mitigated effectively. Figure 5(a) shows a detailed implementation of the cascaded controller.

Although the resonant based HC is a successful solution in terms of high dynamics, it will introduce heavy computation burden and increase parameter tuning difficulties when high order harmonics are required to be compensated (Yang et al., 2015; Yepes, Freijedo, Lopez, & Doval-Gandoy, 2011). According to the IMP (Muraca, 2014; Yang et al., 2015; Zhou et al., 2015), a repetitive controller of a recursive form is also able to achieve zero steady-state error control of any periodic signals at all harmonic frequencies below the Nyquist frequency. Therefore, the repetitive controller can also be adopted as the harmonic controller to enhance the power quality as it is shown in Figure 5(b). In accordance to Figure 5(b), the RC can be expressed as,

$$G_{RC}(s) = k_{rc} \frac{e^{-sT_0}}{1 - e^{-sT_0}} \quad (5)$$

with k_{rc} being the control gain and $T_0 = 1/f_0$ being the fundamental period. Actually, the RC can be further expanded as (Zhou et al., 2015),

$$G_{RC}(s) = k_{rc} \left\{ -\frac{1}{2} + \frac{1}{T_0 s} + \frac{2}{T_0} \left[\frac{s}{s^2 + (\omega_0)^2} + \frac{s}{s^2 + (2\omega_0)^2} + \frac{s}{s^2 + (3\omega_0)^2} + \dots \right] \right\} \quad (6)$$

which implies that the RC is equivalent to the parallel combination of a proportional controller

(i.e., $-k_{rc}/2$), an integrator controller (i.e., $k_{rc}/(T_0s)$), and infinite resonant controllers with an identical control gain $2k_{rc}/T_0$. As a result, the internal models of the DC signal and all harmonics are incorporated in the harmonic compensator to eliminate all harmonics below the Nyquist frequency, being a good alternative for harmonic control. Notably, since the control gains for the infinite resonant controllers are identical, i.e., $2k_{rc}/T_0$, it is then difficult to exclusively tune the control gains for selective frequencies in terms of a good dynamic response. Variant RC based controllers aiming at selective harmonic eliminations have been developed in the literature (Costa-Castello, Grino, & Fossas, 2004; Mattavelli & Marafao, 2004; Yang et al., 2015; Zhou et al., 2006, 2015). However, the frequency adaptability of these variant RC controllers is not covered in this paper.

3.2 Frequency Adaptability Analysis

As it can be clearly observed in (4) and (5), the harmonic rejection capability of the RES and RC harmonic compensators is highly dependent on the resonant frequency, typically being multiple times of the grid frequency estimated by a PLL system. Therefore, both the grid frequency deviation and the estimation accuracy of the PLL system will affect the controller harmonic-attenuation performance. Taking into account those two practical disturbances, the locked angular frequency $\hat{\omega}$ from a PLL system can simply be given as,

$$\hat{\omega} = \omega_0 + \Delta\omega \quad (7)$$

in which ω_0 has been defined previously and $\Delta\omega$ represents the angular frequency deviations induced by grid frequency variations and/or PLL tracking errors.

According to Figure 4, the open-loop $G_{op}(s)$ and closed-loop $G_{cl}(s)$ current transfer functions can then be obtained as,

$$G_{op}(s) = [G_{CC}(s) + G_{HC}(s)] G_p(s) \quad (8)$$

$$G_{cl}(s) = \frac{G_{op}(s)}{1 + G_{op}(s)} = \frac{I_g(s)}{I_g^*(s)} = \frac{[G_{CC}(s) + G_{HC}(s)] G_p(s)}{1 + [G_{CC}(s) + G_{HC}(s)] G_p(s)} \quad (9)$$

with $G_p(s) = G_d(s)G_f(s)$ being the control plant model. In addition, the tracking error ($E_i(s) = I_g^*(s) - I_g(s)$) to the current reference transfer function can be derived as,

$$G_e(s) = \frac{E_i(s)}{I_g^*(s)} = 1 - G_{cl}(s) = \frac{1}{1 + [G_{CC}(s) + G_{HC}(s)] G_p(s)} \quad (10)$$

Subsequently, the frequency response of the error rejection transfer function can be obtained by substituting $s = j\omega$ into (10). Figure 6 shows the frequency responses of the error rejection transfer function $G_e(s)$ where there are only fundamental current controllers (i.e., G_{DB} or G_{PR}). According to (7), it can be seen from Figure 6 that a small frequency variation ($\Delta\omega$) induced by the grid frequency changes and/or PLL estimation errors can significantly contribute to a degradation of the error rejection capability for the PR controller (from negative infinite magnitude to a limited magnitude), especially an increase of the estimated frequency $\hat{\omega}$ (i.e., from $-\infty$ dB to -36 dB). In contrast, the effect of the frequency variation on the DB controller is not significant, since the DB controller is a model-based predictive controller rather than a frequency-dependent controller, as it is shown in (1) and Figure 6. Consequently, the DB controller is more frequency adaptive. Notably, although Figure 6 represents the magnitude response of $G_e(s)$ when only a fundamental-frequency resonant controller is adopted, it can still be concluded that the harmonic rejection capability will

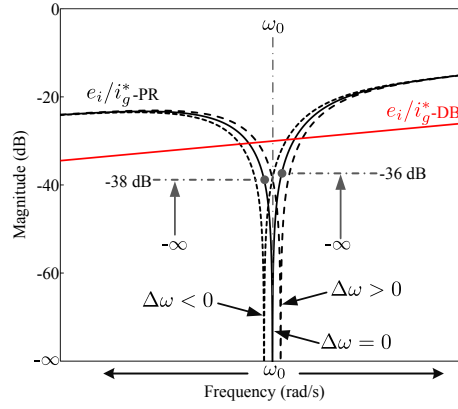


Figure 6. Magnitude response comparisons of $G_e(s)$ only with the fundamental current controllers G_{DB} (red) and G_{PR} (black) in the case of a varying grid frequency and/or PLL control error (i.e., $\hat{\omega} = \omega_0 + \Delta\omega$ with $\Delta\omega \neq 0$ rad/s).

be worsened for the resonant based harmonic controllers (i.e., $\omega_h = h\hat{\omega} = h\omega_0 + h\Delta\omega$), which is further discussed in the following.

In order to achieve a perfect elimination of the harmonics, the harmonic compensator has to approach an infinite gain according to (9) and (10) ideally at those interested harmonics ($h\omega_0$). When there are frequency deviations, the gain of an individual resonant controller $G_{RES}^h(j \cdot h\hat{\omega})$ at the corresponding harmonic frequency ($h\hat{\omega}$) can be expressed as,

$$|G_{RES}^h(j \cdot h\hat{\omega})| = \left| \frac{j \cdot k_{ih} h\hat{\omega}}{-h^2 \hat{\omega}^2 + h^2 \omega_0^2} \right| = \frac{k_{ih}}{|h\omega_0|} \left| \frac{\varepsilon + 1}{\varepsilon^2 + 2\varepsilon} \right| \quad (11)$$

in which $\varepsilon = \Delta\omega/\omega_0$, and it shows that the gain will not be infinite unless $\Delta\omega = 0$. The gain reduction of the resonant controllers is demonstrated in Figure 7, where it can be seen that even a $\pm 0.2\%$ frequency variation can contribute to a significant performance degradation of the resonant controllers (e.g., magnitude changes from ∞ dB to 48.5 dB). It means that the RES harmonic compensator is sensitive to the frequency disturbances caused by the grid frequency changes or PLL control errors.

Similarly, the periodic signal tracking performance of the RC controller will also be degraded in the case of frequency variations, since the RC controller is equivalent to a parallel combination of a proportional controller, an integrator, and infinite resonant controllers according to (5) and (6). Substituting $s = j \cdot h\hat{\omega}$ into (5) yields,

$$G_{RC}(j \cdot h\hat{\omega}) = k_{rc} \frac{e^{-j \cdot h\hat{\omega} T_0}}{1 - e^{-j \cdot h\hat{\omega} T_0}} = k_{rc} \frac{e^{-j \cdot 2\pi h\varepsilon}}{1 - e^{-j \cdot 2\pi h\varepsilon}} \quad (12)$$

Therefore, the magnitude of the RC controller at the harmonic frequencies (i.e., $s = j \cdot h\hat{\omega}$) can be obtained as,

$$|G_{RC}(j \cdot h\hat{\omega})| = \frac{k_{rc}}{\sqrt{2 - 2 \cos(2\pi h\varepsilon)}} \quad (13)$$

which implies that the RC controller can not approach infinite control gain either when there is a frequency tracking error from the PLL system (and/or grid frequency changes), i.e., $\varepsilon \neq 0$. Therefore, the open loop $G_{op}(s)$ will be finite at those harmonic frequencies, leading to an increase in the tracking error $E_i(s)$ of the grid current in accordance to (10). Figure 8 further exemplifies the effect of a frequency tracking error on the harmonic rejection ability of the RC based harmonic compensator. As it can be observed in Figure 8, a remarkable gain drop (from ∞ dB to 28.5 dB) occurs due to a $\pm 0.2\%$ frequency change (i.e., a ± 0.1 Hz frequency variation), and consequently the

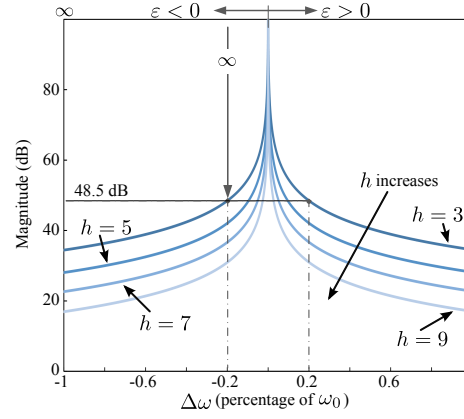


Figure 7. Magnitude of the resonant based harmonic compensator at $s = j \cdot h\hat{\omega}$ ($h=3, 5, 7, 9$) as a function of the frequency variation $\Delta\omega$, where $k_{i3} = 1000$, $k_{i5} = 800$, $k_{i7} = 600$, and $k_{i9} = 400$.

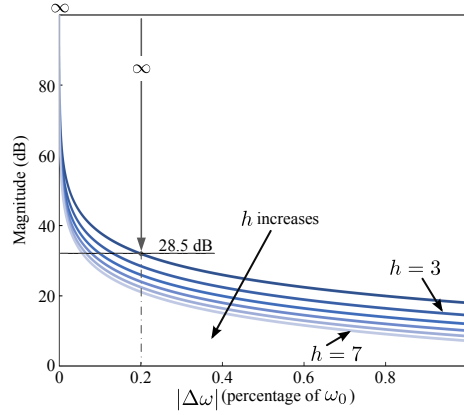


Figure 8. Magnitude of the repetitive based harmonic compensator at $s = j \cdot h\hat{\omega}$ ($h=2, 3, \dots, 7$) as a function of the frequency variation $\Delta\omega$, where $k_{rc}=1$.

harmonic rejection ability is significantly degraded. In addition, high-order harmonics are affected even worse (Steinbuch, 2002) - high-order resonant controller is more sensitive to frequency changes. The above analysis have revealed that the IMP based harmonic compensators are of less frequency adaptability due to their frequency dependency. As for the RC controller, it is also worth to point out that the frequency adaptability will be even lowered when it is digitally implemented in a controller using a fixed sampling rate (Cao & Ledwich, 2002; Yang et al., 2015).

3.3 Enhancing the Frequency Adaptability

As discussed above, in order to achieve a zero-error elimination of the current harmonics even under a variable grid frequency (or a PLL tracking error), the gain of the open-loop system $G_{op}(s)$ should approach infinite according to (8) and (9) in such circumstances. Consequently, the harmonic compensator $G_{HC}(s)$ gain has to be infinite as well when

$$s = j \cdot h\hat{\omega}. \quad (14)$$

This offers a possibility to decrease the frequency sensitivity of the harmonic compensators by feeding back the instantaneous fundamental frequency estimated by an advanced PLL system to the harmonic controllers. As for the resonant based harmonic compensators, an enhancement of the frequency adaptability is presented in Figure 9(a). It can be seen that, by feeding in the PLL estimated frequency, the resonant frequencies of the harmonic controllers will automatically be adaptable to the frequency changes. As a result, infinite gains of the resonant based harmonic

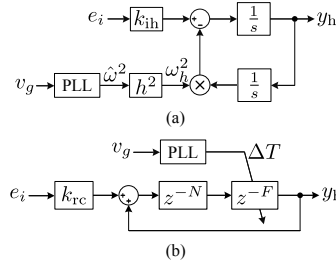


Figure 9. Frequency adaptive harmonic compensators: (a) resonant controllers and (b) repetitive controller.

compensators are ensured in the case of a varying grid frequency.

However, regarding the RC based harmonic compensator, enhancing the frequency adaptability can not be reached by simply feeding back the PLL estimated frequency, since the RC controller is normally implemented in a digital controller of a fix sampling rate (Chen et al., 2013; Costa-Castello et al., 2004; Zhou et al., 2006, 2015). In that case, the RC controller can be given as,

$$G_{RC}(z) = k_{rc} \frac{z^{-(N+F)}}{1 - z^{-(N+F)}} \quad (15)$$

where $N = T_0/T_s$ being an integer and $F = \Delta T/T_s = (T - T_0)/T_s$ is a fractional delay with $T = 2\pi/\hat{\omega}$, in which $\hat{\omega}$ is estimated by a PLL system. As it can be seen in Figure 9(b), enhancing the frequency adaptability of the RC controller requires a proper approximation of the fractional delay z^{-F} induced by the fundamental period changes ΔT . A cost-effective way to approximate the fractional delay is using Finite-Impulse-Response (FIR) filters as discussed in (Yang et al., 2015; Zou et al., 2014). Alternatively, the adaptability can be enhanced by varying the sampling period (Herran et al., 2014), which will ensure an integer of T/T_s but it increases the cost and complexity of the entire digital control system. Notably, from the above discussions, it is known that an advanced PLL system in terms of accuracy and dynamics is crucial for the enhancement of the controller frequency adaptability, especially for single-phase grid-interfaced converters. This should be taken into account in the design phase of the frequency adaptive harmonic controllers.

4. Case Studies

In order to verify the frequency adaptability of the discussed harmonic controllers, experiments have been carried out on a single-phase single-stage PV full-bridge inverter system. Referring to Figures 3 and 4, the single-phase PV inverter has been connected to the grid through an *LCL* filter and an isolation transformer. A commercial programmable AC power source was adopted to emulate the grid, which can arbitrarily produce frequency disturbances. Instead of a real PV string, a commercial DC power source has been used in the experiments. The entire control system was implemented in a dSPACE DS 1103 system. As it is shown in Figure 10, a Second Order Generalized Integrator (SOGI) based PLL algorithm (Blaabjerg et al., 2006; Teodorescu et al., 2011) has been adopted for creating the virtual system v_g^\perp shown in Figure 4. In the case of the resonant based harmonic compensator, only selected low-order harmonics (the 3rd-, 5th-, and 7th-order) have been compensated, as they are the main contributors of the current THD in single-phase grid-interfaced full-bridge inverters. The system and the control parameters have been listed in Table 1.

Figure 11 shows the frequency adaptability of the fundamental-frequency current controllers (i.e., the PR and the DB controllers) and the harmonic controllers when the grid frequency varies in a wider range. It can be seen in Figure 11 that the DB controller is frequency adaptive, while the PR controller is sensitive to frequency deviations. Especially, when the grid frequency increases, the performance of PR controller is degraded significantly, resulting in a poor current THD which may exceed the power quality limitation (e.g., THD < 5% (IEC Standard, 2002; IEEE Standard,

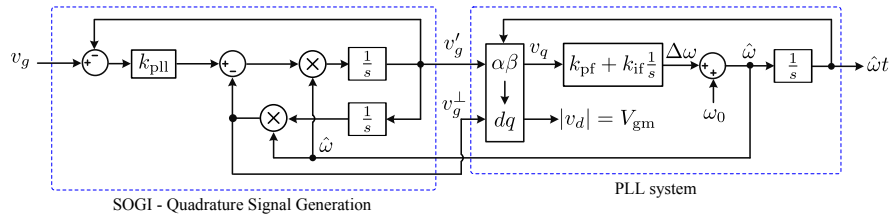


Figure 10. Block diagram of the second order generalized integrator (SOGI) based PLL system used in the experimental tests, where v_g' is the filtered grid voltage, “ $\hat{\cdot}$ ” denotes the estimated value by the PLL system, v_d and v_q are the dq -components of the grid voltage, and v_g^\perp , ω , and ω_0 are defined previously.

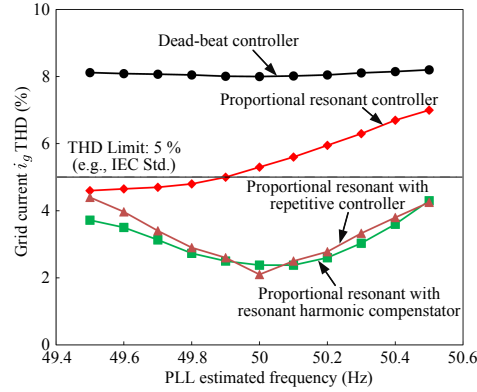


Figure 11. Experimental verification of the frequency adaptability of the dead-beat (DB) and proportional resonant (PR) fundamental controllers, and the PR controller with resonant (RES) and repetitive (RC) based harmonic compensators in the case of a varying grid frequency.

2000)). Moreover, it can be observed in Figure 11 that both the RES and RC based harmonic compensators have poor frequency adaptability, since they are frequency dependent IMP-based controllers. These results are in consistency with the analysis in Figure 6 and also the steady-state performance of the PR controller shown in Figure 12. In addition, it can be seen in Figure 12 that in the case of an abnormal grid frequency, there will be a phase shift between the grid voltage and grid current, and thus the system is not operating at unity power factor mode, which however is preferable for single-phase PV systems. Seen from the experimental results, it is therefore necessary to design frequency adaptive current controllers and harmonic compensators in order to meet the power quality requirements for grid-interfaced power converters.

As mentioned previously in Section 3.3, enhancing the frequency adaptability of the RES controllers can be achieved by feeding back the PLL estimated frequency. To demonstrate this possibility, and also considering the tracking accuracy in the steady-state, the estimated frequency from the SOGI-PLL system as shown in Figure 10 has been feeding back as the instantaneous

Table 1. Parameters of the Single-Phase System Shown in Figure 3.

Parameter	Value
Nominal grid amplitude	$v_{gn} = 220\sqrt{2}$ V
Nominal grid frequency	$\omega_0 = 2\pi \times 50$ rad/s
Reference current amplitude	$I_g = 5$ A
Transformer leakage impedance	$L_g = 2$ mH, $R_g = 0.2$ Ω
LCL -filter	$L_1 = L_2 = 3.6$ mH $C_f = 2.35$ μ F
Sampling and switching frequency	$f_s = f_{sw} = 10$ kHz
DC-link voltage	$V_{dc} = 400$ V
PR controller gains	$k_p = 22$, $k_i = 2000$
Resonant controller gain	$k_{i3,5,7} = 1000$
Repetitive controller gain	$k_{rc} = 1.8$
SOGI control gain	$k_{pll} = \sqrt{2}$
PI controller for the SOGI-PLL system	$k_{pf} = 0.28$, $k_{if} = 13$

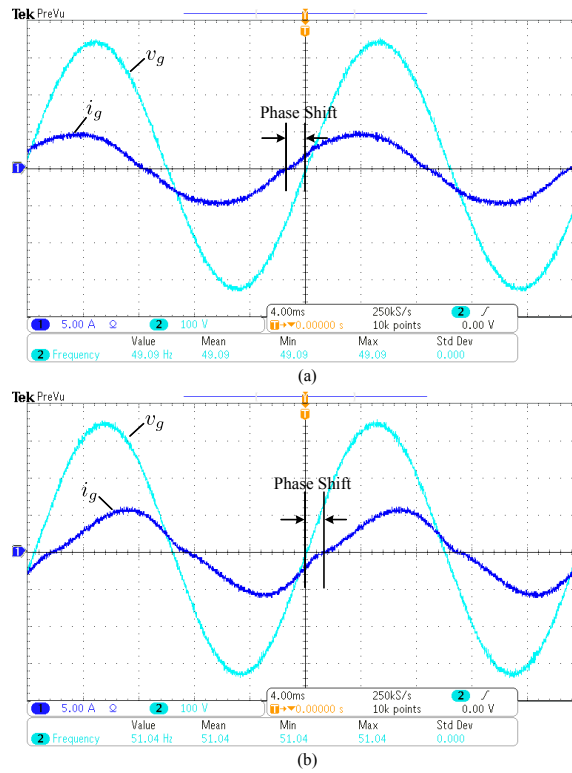


Figure 12. Steady-state performance of the proportional resonant (PR) controller under severer abnormal grid frequencies (grid voltage: v_g [100 V/div], grid current: i_g [5 A/div], time [4 ms/div]): (a) 49 Hz and (b) 51 Hz.

resonant frequencies of the RES based harmonic controller (i.e., $h\hat{\omega}$). Figure 13 compares the dynamic performance of the PR controller with the conventional and the frequency-adaptive RES based harmonic compensators. It can be seen in Figure 13 that by feeding back the SOGI-PLL estimated frequency according to Figure 9(a) the frequency adaptability of the RES based harmonic controllers is improved. Consequently, there will be no phase shift in the steady-state in contrast to the results shown in Figure 12 and the power quality is also improved.

However, in the case of a grid frequency step change, the SOGI-PLL system will also introduce transient frequency variations and delays (Teodorescu et al., 2011). This may further affect the frequency adaptive current controllers as well as the harmonic compensators, which require an accurate knowledge of the grid instantaneous frequency. As it has been validated in Figure 13, there are tracking delays and errors in the SOGI-PLL system, contributing to the dynamic performance degradation of the frequency adaptive controllers. Thus, it calls for more study of tuning the SOGI-PLL system or using more advanced PLL systems in terms of high accuracy, fast response, and immune to background distortions for frequency adaptive current controllers and harmonic compensators applied in grid-interfaced power converters. Nonetheless, improvement of the frequency adaptability has been witnessed in the steady-state when the resonant frequencies for the RES harmonic compensators are adapted to the estimated frequency by a PLL system.

5. Conclusions

Taking the grid frequency variation into account, the frequency adaptability of harmonic controllers for renewable energy systems has been analyzed in this paper. The analysis has revealed that some controllers (e.g. the deadbeat controller) are independent on the grid frequency, while some controllers are very sensitive to grid frequency disturbances. For example, a grid frequency increase of 0.2 Hz can contribute to a significant degradation of the resonant and repetitive based harmonic controllers, thus leading to a poorer power quality of the injected current. Those impacts on

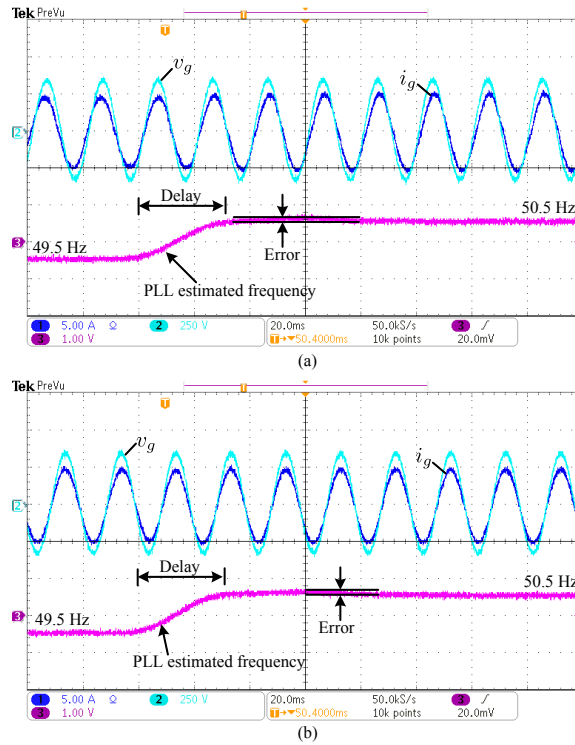


Figure 13. Dynamic performance of the PR controller with RES based harmonic compensators under a grid frequency step from 49.5 Hz to 50.5 Hz (grid voltage: v_g [250 V/div], grid current: i_g [5 A/div], time [20 ms/div]): (a) conventional RES harmonic controllers without feeding back the PLL estimated frequency and (b) frequency-adaptive harmonic controllers with feeding back the SOGI-PLL estimated frequency.

the controller performance have to be taken into consideration in the design phase of harmonic controllers. Case studies on a single-phase single-stage grid-connected PV system have verified the analysis. Possible solutions to improve the frequency adaptability of the discussed harmonic controllers have also been presented and validated experimentally.

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